

Subbarrier fusion reactions with dissipative couplings

K. Hagino ^a, S. Yusa ^a, and N. Rowley ^b

^aDepartment of Physics, Tohoku University, Sendai 980-8578, Japan

^bInstitut de Physique Nucléaire, 91406 Orsay Cedex, France

Using the random matrix model, we discuss the effect of couplings to non-collective states on the penetrability of a one dimensional potential barrier. We show that these non-collective excitations hinder the penetrability and thus smear the barrier distribution at energies above the barrier, while they do not affect significantly the penetrability at deep subbarrier energies. The energy dependence of the Q -value distribution obtained with this model is also discussed.

1. Introduction

The coupled-channels approach has been successful in describing the subbarrier enhancement of heavy-ion fusion cross sections [1, 2]. Conventionally, it takes into account the coupling between the relative motion of the colliding nuclei and a few low-lying collective excitations in the colliding nuclei, as well as transfer channels, which couple strongly to the ground state. High-lying modes, such as giant resonances, and single-particle excitations are not considered usually, since the former simply renormalizes the internucleus potential [3] and the latter is not coupled strongly to the ground state.

However, in recent years, many experimental data have accumulated that suggest a need to go beyond the conventional coupled-channels approach. The examples include the surface diffuseness anomaly in the internuclear potential [4], the steep fall-off of fusion cross sections at deep subbarrier energies [5, 6, 7], a large smoothing of quasi-elastic barrier distribution [8, 9], and the energy dependence of the Q -value spectra for quasi-elastic back scattering [10, 11]. It has been a challenge to account for these new aspects of heavy-ion fusion reactions simultaneously with the coupled-channels framework.

Recently, quasi-elastic scattering cross sections for $^{20}\text{Ne}+^{90,92}\text{Zr}$ systems at backward angles have been measured, which show a considerable difference in the barrier distribution between the two systems [12], that is, the barrier distribution with the ^{92}Zr target is much more smeared than that with ^{90}Zr . The coupled-channels calculations, on the other hand, predict a similar barrier distribution to each other for both the systems, because the rotational excitations of ^{20}Ne play a predominant role. Since those coupled-channels calculations include the collective excitations in the $^{90,92}\text{Zr}$ nuclei, the experimental data strongly indicate that the difference in the barrier distribution for the two systems can be attributed to non-collective excitations in the target nuclei. Notice that the effect of single-particle excitation should be more important in ^{92}Zr , compared to a $N = 50$ magic

nucleus, ^{90}Zr .

In this contribution, we shall discuss the effect of single-particle excitations on heavy-ion reactions, that have been ignored in the conventional coupled-channels approach. To this end, we compute the penetrability for a one dimensional two-level system in the presence of a coupling to dissipative environment described by a random matrix model. The random matrix model was originally developed by Weidenmüller and his collaborators in the late 70's in order to describe deep inelastic collisions for massive systems [13]. Here we shall use a similar model, and solve quantum mechanically the coupled-channels equations of a large dimension. See Refs. [14, 15, 16] for earlier attempts, which however did not use the random matrix model.

2. One-dimensional barrier penetrability with random matrix model

In the random matrix model, one considers an ensemble of the coupling matrix elements, $V_{ij}(x)$, in the coupled-channels equations, which are assumed to follow the Gaussian Orthogonal Ensemble (GOE) [13]. That is, they have a zero mean, $\overline{V_{ij}(x)} = 0$, and the second moment is given by

$$\overline{V_{ij}(x)V_{kl}(x')} = (\delta_{i,k}\delta_{j,l} + \delta_{i,l}\delta_{j,k}) \frac{w_0}{\sqrt{\rho(\epsilon_i)\rho(\epsilon_j)}} e^{-\frac{(\epsilon_i - \epsilon_j)^2}{2\Delta^2}} \cdot e^{-\frac{(x-x')^2}{2\sigma^2}} \cdot e^{-\frac{x^2+x'^2}{2\alpha^2}}, \quad (1)$$

where $\rho(\epsilon)$ is the level density.

We apply this model to a one-dimensional system [17], in which we consider a Gaussian potential barrier with the height of 100 MeV [18, 19]. In order to take into account the quasi-continuum single-particle spectrum, we discretize it [20] from 3 MeV to 13 MeV with an energy spacing of 0.05 MeV (in this way, we include 200 single-particle channels). In order to take an ensemble average, we generate 20 random matrices and perform coupled-channels calculations 20 times for each energy. In addition to the single-particle levels, we consider also a collective level at 1 MeV, whose coupling form factor is given by a Gaussian function [18, 19]. The coupling strength to the collective state is set to be the same for all the samples in the random ensemble.

The top panel of Fig. 1 shows the penetrability thus obtained (the solid line), in comparison to that without the couplings to non-collective states (the dashed line). The figure also shows by the dotted line the result of a single-channel calculation. The effect of the non-collective couplings mainly appears at energies above the barrier, where the couplings hinder the penetrability. The middle panel shows the barrier distribution [1, 2], defined as the first derivative of the penetrability. In the absence of the non-collective couplings, the barrier distribution has two peaks, corresponding to the two eigen-barriers generated from superpositions of the ground and the collective states. When the non-collective couplings are switched on, the higher peak is smeared significantly, although the structure of the lower peak remains almost the same. The bottom panel shows the logarithmic slope of the penetrability [5], which provides a useful means to investigate the deep subbarrier behavior of the penetrability. One can see that the logarithmic slope is not altered much by the non-collective couplings, indicating that the steep fall-off phenomena of deep subbarrier fusion cross sections do not seem to be accounted for by the present mechanism (see also Ref. [21]).

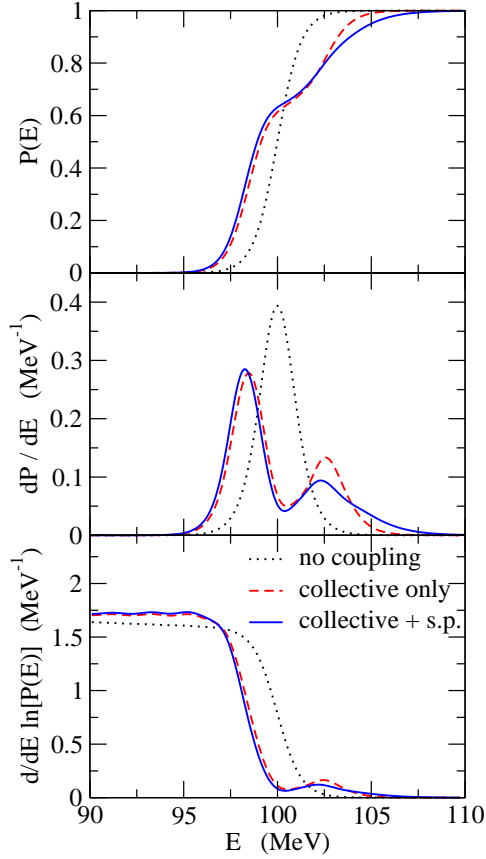


Figure 1. The penetrability (the top panel), the barrier distribution (the middle panel), and the logarithmic slope of the penetrability (the bottom panel) obtained with the random matrix model.

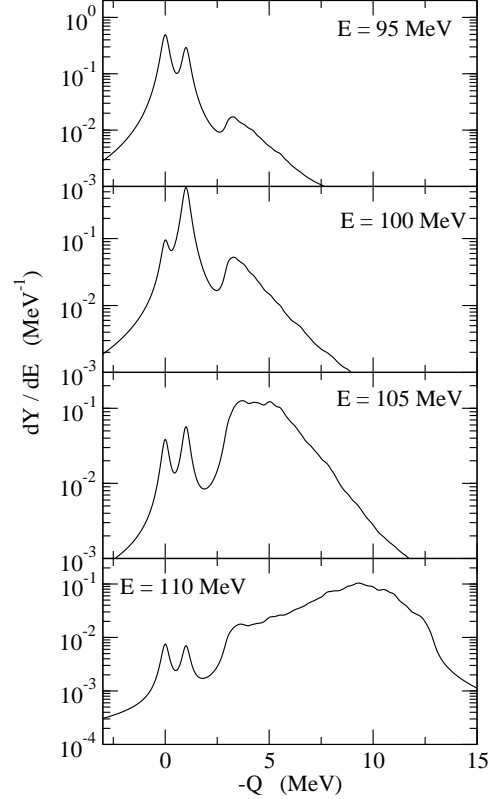


Figure 2. The energy dependence of the Q -value distribution defined with the reflected flux. The peaks at $Q=0$ and -1 MeV correspond to the elastic scattering and the excitation of the collective state, respectively.

Figure 2 shows the Q -value distribution obtained with the reflected flux in the solution of coupled-channels equations. We have smeared the discrete distribution with a Lorentzian function with the width of 0.2 MeV. At energies below the barrier, only the elastic and the collective channels are important. As energy increases, one can clearly see that the single-particle excitations gradually become important, in accordance with the results shown in Fig. 1. One can also define the Q -value distribution with the transmitted flux (not shown). Our calculation indicates that the Q -value distribution obtained with the transmitted flux is much less sensitive to the non-collective couplings compared with the Q -value distribution defined with the reflected flux, suggesting that quasi-elastic scattering is more sensitive to the single-particle excitations than fusion.

3. Summary

We have applied the random matrix model to a one-dimensional barrier penetrability in order to discuss the effect of single-particle excitations. We have shown that the effects of non-collective excitations mainly affect the above barrier behavior of the penetrability, that is, they hinder the penetrability and smear the barrier distribution. On the other hand, the low energy behavior does not appear significant. The coupled-channels approach with the random matrix model enables one to compute the Q -value distribution. We have shown that the single-particle excitation gradually becomes important as energy increases.

In this contribution, we have used a schematic one-dimensional model. It will be an interesting future project to apply this model to realistic systems, and investigate the effect of non-collective excitations on quasi-elastic barrier distributions. A quantum mechanical description of deep inelastic collisions using the present model will also be of interest.

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